Primary Factors Effecting Clouds and Precipitation Due to Urbanization

MR3421

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Introduction. Urbanization is not a new idea. Man has congregated in cities for protection and economic advantages since the dawn of civilization. Chances are these groups of humans have always inadvertently modified their weather. Anthropologists tell us early man probably built their dwellings out of natural materials. But they did deforest, scrape or wear away trails into dirt roads, operated ovens for pottery or cooking, and a host of other activities. These served to accomplished two things; city dwelling became more advantageous, and city life attracted others. The idea caught on and man began to modify their weather…on a small scale.

Fast forward to today, post industrial revolution, cities and suburbs are bulging with humans. Despite this being the information age, North America still has an industrial center in nearly every city containing more than a few thousand people. 65% of the human population in North America live in large metropolitan areas. [i]

The degree to which we modify our weather due to urbanization is orders of magnitude greater than early man; not just because of population. There are other factors involves that we are just beginning to recognize. We've become quite advanced at modifying our weather.

The problem of inadvertent weather modification take many forms. This paper will address weather modifications due to urbanization, mainly resulting from the urban heat island effect. We'll ignore other inadvertent weather modifications due to agricultural land use, water redirection, airplane contrails and even military chaff [ii].

Urban Climate Change; The Basics. Comparing urbanization levels of today to those just 150 years ago denotes a dramatic increase. Urban areas and population continue to grow and predictions are that our degree of modification of the weather will also grow. The primary effect of these ever-growing urban centers is on ambient temperature. Almost everyone notices that it's hotter downtown. There exists a relationship between population and temperature.

Table one suggests a linear relationship. Another important factor effects the degree of

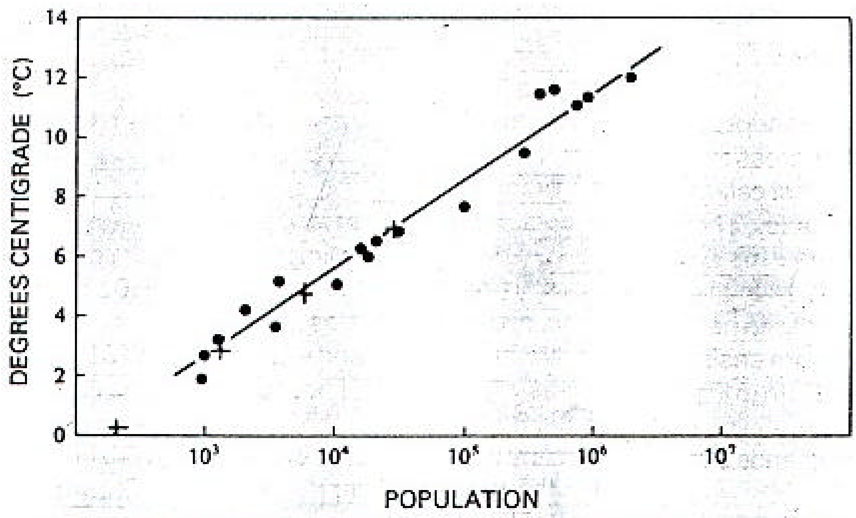

FIG. 1. Relation of maximum urban heat island to the population of North American cities (from Landsberg 1981).

warming in populated area; our "modern" building supplies. Simply put, we've gotten more efficient at raising the temperature of our urban areas. Temperatures in urban areas are commonly 2-8 degrees F higher than surrounding rural areas. [iii]

Estimates of future temperature increases vary. How many generations will pass until urban areas are too uncomfortable for inhabitants during the warm months?

(Table 2)

	Winter	Summer
Cleveland	1.0°	2.8°
Boston	1.6°	2.6°
Washington, D.C.	0.9°	2.4°

Common use of cheaply-manufactured low albedo construction materials exacerbates the problem. Most roads are asphalt - black. Roofs are commonly dark or even tar covered. The albedo of trees and grass is typically .15-.18 to .25 .3 respectively. On the other hand, the albedo of asphalt is .02 to .2 Low albedo surfaces absorb the sun's radiation, heat up and pass the heat to the ambient air, warming it. [iii]

Urban weather modification as it pertains to clouds and precipitation are closely related to the change in heat and moisture flux. Common urban heat island effects are increased precipitation and clouds on the downstream side of urban areas, especially on weekdays. Studies have shown that thunderstorms and hail are more common and more intense downstream of urban areas. Relative humidity is commonly lower in cities. Fog occurs more often in some cities, but is typically less dense. We will discuss theories to explain these occurrences.

While thermal flux/modification drive many of the weather modification phenomena, chemical reactions and byproducts contribute as well. Pollutants such as fossil fuel combustion by-products play a part in producing cloud droplet condensation nuclei and smog. We will deal with these effects only briefly. The allowable length of this paper precludes me from dealing with chemical reactions which play a role in modifying levels of ozone, NO_2 and other smog constituents.

Urban Heat Budget. For the purposes of this treatment, let me define the urban boundary layer as the general, local mesoscale feature whose characteristics are governed

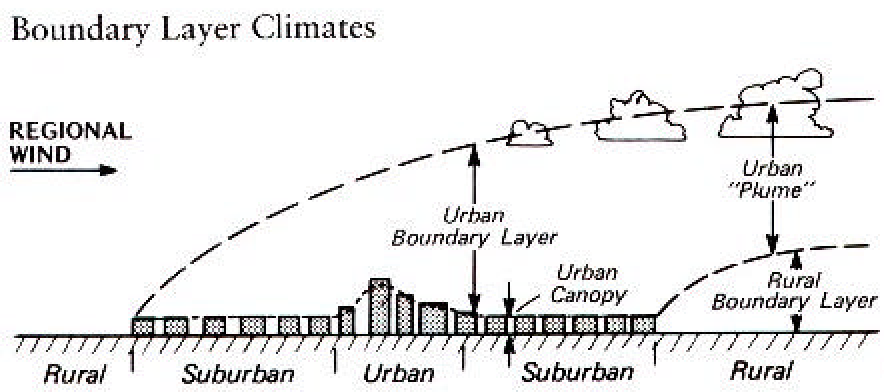

Figure 1 Schematic representation of the urban atmosphere illustrating a two-layer classification of urban modification (after Oke, 1976a).

by the nature of the urban surface. The urban canopy layer is defined as the layer beneath building tops.[iv]

This brief treatment of the urban energy (heat) balance is encompassed by the urban boundary layer and includes the canopy. The balance is represented by the following equation.

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \qquad \text{Equation 1}$$

Variable	Definition
Q^*	Net radiation
Q_F	Heat sources associated with combustion (Anthropogenic heat flux density)
Q_H	Sensible heat flux density
Q_E	Evapotranspiration
ΔQ_S	Heat Storage changes in the ground
ΔQ_A	Net horizontal transfer of sensible and latent heat

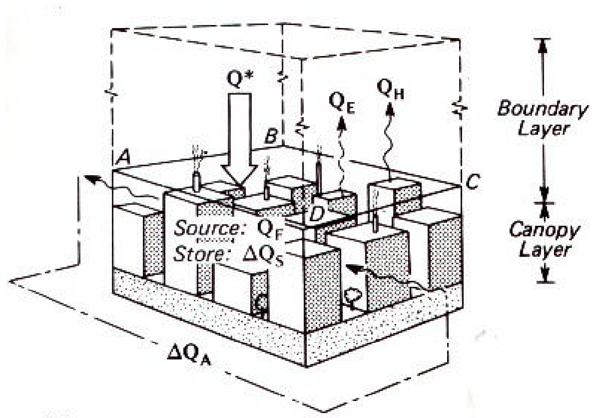

Figure 2

Note that Q_F is an energy mass flow that is directly controlled by human decisions. Q_F is rhythmic according to heights and falls of human activity. Q_F is tightly coupled with time of day and is largest during daytime hours. The separation between Q* and Q_F is variable. For instance, in Anchorage Alaska, Q_F is commonly higher than Q*, however, in Los Angeles, Q* almost always overpowers Q_F . Q_F is most directly tied to population. ΔQ_A is an advective term. Studying equation (1) one can understand the differences between the energy balance between urban and rural scenarios.

With the addition of $Q_{F,}$ it's easy to understand why thunderstorms often form on the downwind side of large urban areas. With the addition of urban heat, the ambient air warms, rises and is carried downwind by the predominant flow. If the additional heat is sufficient to produce unstable conditions, thunderstorms develop. If conditions are already unstable, an influx of heat can force higher cloud tops making thunderstorms more severe, often making them hail-producers. [iv]

Examples abound, but here is a figure depicting precipitation for St. Louis:

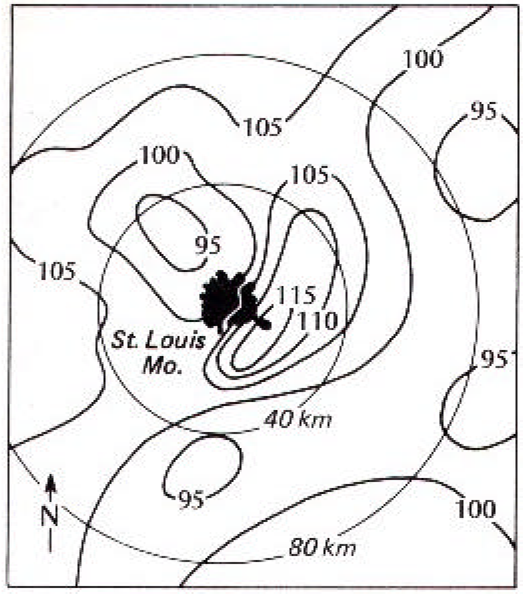

Figure 3

For another aspect, let's look at the urban water balance.

Urban Water Balance. Heat is a great weather catalyst, but for a complete treatment, moisture must be considered. Lets consider the following equation:

$$P + F + I = E + \Delta r + \Delta S + \Delta A \qquad \text{Equation 2}$$

Variable	Definition
P	Precipitation
F	Water release from combustion
I	Urban water supply (rivers and reservoirs)
E	Evaporation
Δr	Urban runoff
ΔS	Subsurface storage
ΔA	Advection of water through sides of volume

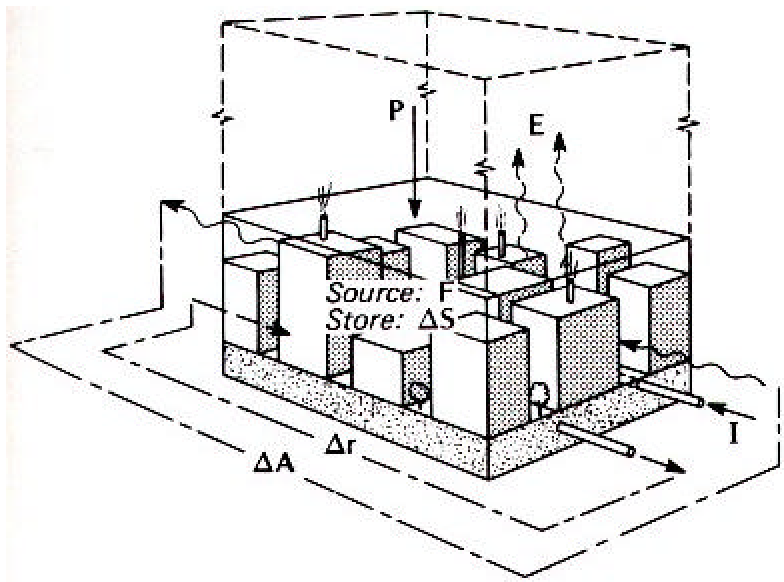

Figure 4

The urban water balance has two terms not normally found in rural areas. Large amounts of water vapor are released when fossil fuels are burned. Importation of water from water sources like river and lakes is easily monitored. There are seasonal peaks (summer) as well as daily peaks (morning and evening) in water consumption by humans. There are no rural counterparts for F and I. Both evapotranspiration (E) and sub-surface storage (ΔS) are less in the city. Runoff (Δr) is greater in the city as well. Surfaces are hard, usually impermeable which support efficient runoff. Storm drains are common.

Although humidity differences between rural and urban canopies are small, the consensus is that urban canopy air is usually drier by day but moister by night. In the rural day, evapotranspiration is high, consequently in the early evening rural air cools more quickly and becomes more stable. The instability resulting from the lingering warmth of urban air contributes to convective storms downstream of urban areas.

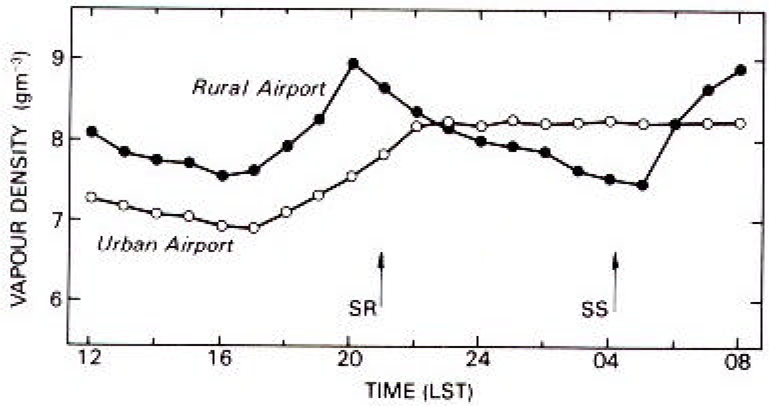

Figure 8.17 Daily variation of humidity on 30 fine summer days in and near Edmonton, Alberta (after Hage 1975).

In cold climates, the city is often more humid during the day owing to very little evapotranspiration from dormant plants, while the city has vapor input from combustion.

City Fog. Fog in cities can be indeed thick at times. However, usually the frequency of dense fog is less in cities. The improvement is due to the heat island effect (increased temperature) and the abundance of condensation nuclei. The increased number of CCN result in greater competition for vapor hence a larger number of smaller droplets.

Urbanization in high latitudes produce episodes of ice fogs. Vapor released into the air when the temperature is less than -30 degrees C results in a fog of ice crystals. Due to a very low saturation vapor pressure, the ice crystals form on combustion byproducts from heating fuel, industrial and aircraft fuel, etc.

Cloud Formation. We've already noted that within the urban boundary layer, we tend to have rising air due to the urban heat island effect. During the evenings we tend to have higher moisture content that during the day. Another factor effects cloud formation downwind of urban areas; the abundance of cloud condensation nuclei. Pollutant particulate matter from industrial and transportation burning of fossil fuels and a host of other pollution sources.

Current Research. Volumes have already been written, and volumes yet to be written on the effects of inadvertent weather modification due to urbanization. In general, the research in this area is focused on the heat budgets of cities and how we can "cool" our cities or constrain temperatures within urban areas. A great deal of current literature involves mapping or heat fluxes of urban area. A large urban heat modeling project was done in Tokyo, NASA is mapping cities like Atlanta, Chicago, Salt Lake City, etc. Most of the more recent work is not looking at the effects on clouds and precipitation as this aspect is considered fairly well understood. Research focuses on solving the potential future problem of linear growth of population and heat in urban areas by using cool materials, planting more trees or building more parks.[iii]

Summary. The problem will surely worsen before it improves. Old norms and economic hurdles must be overcome to encourage builders and developers to use "cool" products and plant trees. Government must be a part of any change.

The urban boundary layer experiences an energy and moisture flux different than rural boundary layers. These differences lead to cloud and precipitation differences near (mostly downwind) of large urban areas. The influx of heat into the boundary layer aids instability and creates or intensifies thunderstorms downwind. Similarly, urban air is slow to cool in the evenings producing a boost to instability thus convective activity is given a boost from urban humidity flux as well. While there are other anthropogenic chemical and wind effects that effect other aspects of urban weather the aim of this paper was to address the primary man-made effects on clouds and precipitation.

[i] Changnon, Stanley, "Inadvertent Weather Modification in Urban Areas" Lessons for Global Climate Change", Bulletin of the American Meteorological Society Vol. 73 No. 5, May 1992

[ii] Maddow, Robert A. et al, "Intense Convective Storms with Little or No Lightning over Central Arizona: A case of Inadvertent Weather Modification?" Journal of Applied Meteorology, Vol 36, pp302-314, April 1997

[iii] Chicago Urban Fabric Analysis Project http:// www.civil.nwu.edu/acbm/Giunipero/

[iv] Oke, T.R., Boundary Layer Climates, University Paperbacks, 1978